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A hydrogeomorphic assessment of 21st Century floods in the UK

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Abstract

The occurrence of devastating floods in the British uplands during the first two decades of the 21st century poses two key questions: (1) are recent events unprecedented in terms of their frequency and magnitude; and (2) is climate and/or landuse change driving the apparent upturn in flooding? Conventional methods of analysing instrumental flow records cannot answer these questions because upland catchments are usually ungauged, and where records do exist they rarely provide more than 30-40 years of data. In this paper we analyse all lichen-dated upland flood records in the UK to establish the longer-term context and causes of recent severe flooding. Our new analysis of torrential sedimentary deposits shows that 21st century floods are not unprecedented in terms of both their frequency (they were more frequent before 1960) and magnitude (the biggest events occurred during the 17th-19th centuries). However, in some areas recent floods have either equalled or exceeded the largest historical events. The majority of recent floods have been triggered by torrential summer downpours related to a marked negative phase of the summer NAO between 2007 and 2012. It is of concern that historical data suggests there is far more capacity in the North Atlantic climate system to produce wetter and more prolonged flood-rich periods than hitherto experienced in the 21st century. Looking forwards, an increased likelihood of weather extremes due to climate change means that geomorphological based flood series extensions must be placed at the centre of flood risk assessment in the UK uplands and in similar areas worldwide.

Key words:

21st century floods, British uplands, lichenometry, NAO, flood risk management

1. Introduction

Violent rainstorms and severe floods have characterized many European river catchments since the beginning of the 21st century (Hall *et al*., 2014), leading to fatalities and damage to properties and infrastructure, all of which equate to severe financial costs (Kundzewicz *et al*., 2014). The occurrence of devastating 21st century floods raises two key questions: (1) are recent events unprecedented in terms of their frequency and magnitude; and (2) is climate and/or landuse change driving the apparent upturn in flooding? Answering these questions requires long datasets so that recent severe floods can be placed in their long-term context, and the full range of natural variability assessed. It is at this point that analyses of event rarity very commonly encounter problems. This is because although some rainfall records do extend for a century or more (Alexander and Jones, 2000; Cioffi *et al*., 2014), the average length of river flow gauging is much shorter (~35-40 years in the UK). As a result, flood frequency and magnitude data may be unreliable and in many ungauged upland catchments, unavailable. When large floods do occur, they are often reported as 'unprecedented' or 'the biggest in living memory', despite the questionable accuracy of these statements (Foulds *et al*., 2012).

Fluvial systems record episodes of extreme wet weather, floods and climatic change (*cf*. Macklin *et al*., 2012) in the form of torrential sedimentary deposits, principally boulder-berms and debris flows[1] (Innes, 1983; Wells and Harvey, 1987; Macklin *et al*., 1992; Macklin and Rumsby, 2007; Foulds *et al*., 2014a, 2014b). It is through the investigation and dating of these deposits that geomorphologists can fill the knowledge gap concerning the longer-term context and likely causes of upland flooding. In the UK, a combination of lichenometry and palaeohydraulic reconstruction methods (Q estimates based on boulder transport equations) have been used to assess flood frequency and magnitude over periods approaching 300 years (Macklin *et al*., 1992; Merrett, 2001). The application of these methods in small upland UK catchments (typically <10 km^2) over the past 25 years has transformed our understanding of extreme flood events and their wider climatic context (Macklin and Rumsby, 2007; Foulds *et al*., 2014b). In fact, the British

[1] We define boulder-berms and debris flows as the product of 'geomorphologically effective' floods.

boulder-berm and debris flow flood record, comprising 556 dated water-lain deposits and 305 debris flow units, now provides one of the longest and most complete databases of upland flooding in Europe. Interrogation of this type of long-term hydrogeomorphic data provides a unique opportunity to assess the context of recent flood problems and develop a better understanding of likely future flood risk in response to climate change. The latter is especially important because down-scaled regional climate models have been shown to perform poorly in small, steep catchments (Smith *et al*., 2014), where flash floods may occur at space and time scales that conventional observation systems are not able to monitor (Borga *et al*., 2014).

This paper has three primary objectives: 1. To update the British boulder-berm record, as first published by Macklin and Rumsby (2007), in order to contextualise recent (21^{st} century) 'extremes'; 2. To evaluate flood chronologies in the context of climatic controls, in order to facilitate a better understanding of flood drivers and how these have changed in the past, and may change in the future due to anthropogenic climate change; and 3. To propose some practical applications of palaeohydrological studies in flood risk assessment and how these can be integrated in catchment management, including flood protection.

2. Study catchments and methods

Table 1 summarises the physiographic characteristics of upland UK catchments discussed in this paper and Figure 1 shows study site locations with respect to extreme rainfall precipitation variability areas, as defined by Jones *et al*. (2014). Chronologies for two types of flood event are discussed in this paper: (1) boulder-berms deposited by rivers flowing under Newtonian flows (English and Welsh catchments), which are located in steep mountain torrents (typically ~10% channel bed slope); (2) debris flows formed under non-Newtonian conditions. Typically, debris flows occur on very steep mountainsides (>10% slope) and they have been most intensively studied in Scotland. All of the study catchments have been affected by Pleistocene glaciation and periglaciation. This has left a legacy of boulder-rich drift mantled slopes fringing river channels; and these deposits constitute an important sediment source during extreme flood events.

The British uplands have a temperate-maritime climate and can be affected by prolonged periods of frontal rainfall at any time of the year (Webb, 1987), with slow moving convective storms in summer months. There is the tendency for colder average winter temperatures in northern England (Manley, 1936) and Scotland compared to southern Britain (*e.g.*, Dartmoor), and a correspondingly greater number of days with snow lying (see Holden and Rose, 2011 and Met Office, 2011). As a result, snowmelt combining with rainfall is an important extreme flood generator in northern Britain (Archer, 1981).

All studies reviewed in this paper used indirect lichenometry to date sedimentary deposits. Full details of the lichenometric methods used and their limitations can be found in Rumsby (1991), Merrett and Macklin (1999) and Foulds *et al*. (2014a, 2014b). For water-lain flood deposits, relative flood magnitude has been assessed using b-axis data of the average of the three, five or ten largest clasts (Table 1; Rumsby and Macklin, 2007). Several studies have also estimated discharge using Carling's (1986) method, which is based on the critical shear stress required for coarse sediment transport derived from field data collected in a small, steep upland UK catchment. Detailed appraisals of this method can be found in Rumsby (1991), Merrett (2001) and Foulds *et al*. (2014b).

3. Upland flood chronologies (boulder-berms)

The timing of geomorphologically effective floods in catchments located in the North West and Solway extreme precipitation variability areas, and those located in Mid Wales and the South West, show varying degrees of synchrony (Figure 2). In the North Pennines, three periods of enhanced flooding are evident from 1780-1820, 1840-1880 and 1920-1960. Similar decadal and multi-decadal trends are evident in the Yorkshire Dales and Lake District, although in the former area extreme flooding continued later into the 20th century (1960s and 1980s). Catchments in South West England (Dartmoor) and south Wales (Brecon Beacons) also show a mid to late 19th century phase of flooding, followed by flooding in the early to mid-20th century. Records from Mid Wales and the South West, however, show little evidence of flooding at the turn of the 19th century (Foulds *et al*., 2014a, 2014b). New data from the Central Brecon Beacons (Figure 2; Matthews, 2015) also highlight some local and regional-scale differences in flood timing. For example, although the timing of early 20th century flooding (1910s) is very similar in the Cambrian Mountains and Brecon Beacons, the latter area is characterised by flooding in the 1990s, which is quite different to the rest of Wales and the UK. Analysis of annual maximum gauged flow data in the Brecon Beacons confirms that large floods occurred in March and October 1998, the latter setting new flow records on some rivers (CEH, 1998).

For England and Wales as a whole, two major flood-rich periods are evident over the last 200 years. These are 1840-1890 and 1910-1950, punctuated by a reduction in flood activity centred on 1900. The most striking feature of the British boulder-berm record is the sharp mid to late 20th century decline in flooding, reaching its nadir in the 1990s. This pattern is evident throughout the British uplands (the one exception being the central Brecon Beacons), but the trend has reversed since 2007, with several catchments in northern England (North Pennines) and Wales (Brecon Beacons and Cambrian Mountains) experiencing large floods. The significance of these events is discussed below.

3.1. Flood magnitude in the 21st century

A series of large floods occurred in the UK uplands in the early 21st century, beginning with the North Cornwall and North Yorkshire events of 2004 and 2005 (Roca and Davison, 2009; Cinderey, 2005). These were followed by a flood-rich period (especially summers) bracketed by the very wet years of 2007 and 2012 (Marsh, 2008; Parry *et al*., 2013). Macklin and Rumsby (2007) commented that it was too early to say if the North Cornwall and North Yorkshire events were an indication of changing conditions in the British uplands; eight years later, our new geomorphological analysis shows a transition from a well-documented multidecadal flood-poor period in the late 20th century (Macklin and Rumsby, 2007), to the beginnings of a flood-rich phase since 2007 (Foulds *et al*., 2014b; Figure 2).

3.1.1. North Pennines

In July 2007 a torrential rainstorm and flood generated boulder-berms in Thinhope Burn (Milan, 2012), which contrasts sharply with the floodless 1980s and 1990s (Figure 3a). In terms of flood magnitude, clast measurements indicate that this flood was of very similar size to the largest historical events recorded in the catchment (1766, 1929) and marks an upturn from smaller floods in the 1970s.

3.1.2. Brecon Beacons and Cambrian Mountains

In the central Brecon Beacons a flood on 5th September 2008 was the largest event since the 1960s, and b-axis measurements on one boulder-berm suggest that it was largest flood recorded in the catchment (Figure 3b). The 2008 flood was triggered by a torrential localised downpour of ~100 mm of rain in ~1 hour; a detailed account and photographs of this event are available online at UKweatherworld (2008). In contrast, the June 2012 flood in Mid Wales (Figure 3c) was of similar magnitude to historical events: on one river – the Leri - it was the largest flood since June 1935 (Foulds *et al*., 2012, 2014b).

3.1.3. Dartmoor and South West England

Catchments draining central and northern Dartmoor (Foulds *et al*., 2014a) were resurveyed to assess the landscape impact of a series of notable rainfall events, especially during autumn 2012 and winter 2013/2014. Despite severe flooding in many large lowland catchments, no new headwater berms were evident (Figure 3d) because these were long duration, low intensity rainfall events, which are less effective in generating extreme unit discharges in small catchments. In the wider South West region, the 2004 River Valency (Boscastle) flood was the largest event since the 1952 Lynmouth disaster, but a larger Lynmouth flood occurred in 1770 (Clark, 2001). Three other severe floods also affected North Cornwall in the 1950s, notably June 1957 (Burt, 2005) and June 1958; during the latter event the River Valency at Boscastle is reported to have risen 15 feet (4.57 m) in 20 minutes, leading to one fatality (The Times, 1958).

3.1.4. Yorkshire Dales

The last *known* major geomorphologically effective flood of the 20th century in northern England took place in January 1995 (Merrett, 2001; Johnson and Warburton, 2002; Brewer *et al*., 2011) – an event which set new flow records in North East England and parts of North Yorkshire (CEH, 1995). However, documentary evidence and instrumental data (discharge and stage) do show that large floods have occurred in the region since 2007 (Table 2). On the River Swale (piedmont reach) the maximum discharge during a flood on 25th September 2012 was 4% larger than January 1995. A severe rain-on-snow flood in the Swale uplands on 8th December 2011 (Figure 4) caused considerable damage and was reported in local newspapers as the 'biggest in living memory'. Stage data (Table 2) confirm this was the biggest flood of the last 19 years (1996-2015) on the upper Swale. A torrential storm and flash flood in Coverdale (July 2014) also had major geomorphological impacts, depositing boulder-berms in several headwater catchments (Warren, 2014). Detailed investigations are now needed to resurvey the Yorkshire Dales area.

3.1.5. Flood magnitude since the 17th century

The longer-term context of flood magnitude in the British uplands is one of a general decline since the late 19th/early 20th century (Figure 3). Catchments with the longest records (Northern Pennines, Dales and Dartmoor), recorded some of their largest floods in the 17th, 18th and early 19th centuries. However, the downward trend in flood size was interrupted by several large events that occurred between 1890 and 1920 (Yorkshire Dales and Dartmoor) and 1920 to 1950 (Northern Pennines and Cambrian Mountains). In most upland catchments 1960 appears to be an important break point in terms of flood magnitude. We discuss the potential reasons for this decline and subsequent 21st century increase in flood activity in sections 4.1 and 4.2.

3.2. Debris flows

The longest UK debris flow record is located in the Cairngorms (Figure 5), where activity increased markedly after 1810 and there were two multi-decadal length periods of flooding in the late 19th century and from 1920 to 1950, followed by a major peak in the 1970s. The Glencoe debris flow record is similar to the Cairngorms, the exception being it has only one (albeit prolonged) period of multi-decadal flooding from 1890 to 1950, followed by a similar 1970s peak of activity. In northwest Scotland, the An Teallach record is markedly different, with reduced flooding between 1910 and 1970; a period characterised by high rates of flooding elsewhere in Scotland. High rates of activity are evident from 1890-1910, and during the 1970s, similar to the other Scottish sites. Although there are no published post-1980 lichen chronologies of debris flow activity in Scotland, numerous events have been well-documented since the late 1990s (Winter *et al*., 2005, 2006, 2010).

Debris flow records in Wales are more difficult to interpret due to the small number of dated deposits and limited spatial scale of investigated sites (three valleys in total). The majority of debris flow events occurred between 1890 and 1930; however, there are regional differences with flooding between 1970 and 2000 in North Wales, compared to 1820 to 1960 in South Wales (Figure 5). The principal difference in the timing of debris flows in Wales compared to Scotland is the absence of major activity in the late 20th century. An important caveat is that although lichenometric analyses of debris flows allows periods of exceptional activity to be identified, there is a tendency for older deposits to be buried by younger flows (Ballantyne, 2004).

4. Rainfall, extreme floods and the North Atlantic Oscillation

In the UK the relationship between hydrological variables and the widely used station-based NAO index (Jones *et al*., 1997) are relatively well understood (Wilby *et al*., 1997; Fowler and Kilsby, 2002; Burt and Howden, 2013). For seasonal and monthly rainfall and river flows there are strong positive correlations with the NAO in northern and western locations, especially during the winter half year (Oct-Mar), and with increasing altitude (Burt and Howden, 2013). These patterns weaken during the spring and summer away from the far NW of Scotland, where extra-tropical cyclones continue to influence the weather and river discharge (Burt and Howden, 2013; Lavers *et al*., 2013). In contrast, extreme floods in small mountain catchments tend to have a closer association with negative NAO index values (Macklin and Rumsby, 2007; Foulds *et al*., 2014b). There are three key reasons for this:

1. Positive autumn/winter NAO index values in the uplands are usually associated with periods of prolonged (orographically enhanced) frontal rainfall (*e.g*. autumn 2000, 2012). These storms often yield very high daily and multiday rainfall totals but rarely produce short duration rainfall totals approaching the 40 mm hr^{-1} intensity threshold (usually convective in nature and highly localised) characteristic of UK 'flash floods' (Archer and Fowler, 2015). Exceptionally intense rainstorms are more typical of –NAO conditions during the summer (Foulds *et al*., 2014b).

2. During the summer the NAO changes to more of a Greenland-UK pressure pattern seesaw (Cropper *et al*., 2015), as opposed to winter Azores-Iceland setup. This dynamic movement is best captured by the SNAO index of Folland *et al*. (2009), which is derived from gridded mean sea level pressure data. Negative SNAO index values indicate a southerly displacement of the north Atlantic storm track and cyclones towards the UK. Note that the probability of a cyclone over the British Isles is highest during late summer (Matthews *et al*., 2015), giving the potential for slow moving torrential downpours and boulder-berm generation (Foulds *et al*., 2014b). Positive SNAO index values are associated with drier, warmer and sunnier weather in the UK and NW Europe.

3. Although usually drier than average, –NAO winters are often snowy, which increases the likelihood of severe rain-on-snow floods as polar or continental air masses are displaced by mild and wet Atlantic air masses (*i.e.* transition from –NAO to +NAO). These transitional phases are critical because snow-water equivalents can exceed 100 mm in the UK uplands and cause extreme runoff in combination with heavy rainfall (Archer, 1981). In terms of boulder-berm generation, prolonged periods of winter cold may also increase sediment supply from slopes to river channels (Clark, 1970).

4.1. Extreme winter floods (boulder-berms)

Two periods characterised by negative NAO values occurred between 1740 and 1830 and between 1960 and the early 1980s (Figure 6a). The former period includes a phase of extreme flooding in northern England between 1770-1820, characterised by the highest number of mean daily temperatures below 0^oC in the CET record

(Jones and Hulme, 1997) and below average rainfall (Figure 6b). Low NAO values from 1960 to the early 1980s do not appear to have left a significant geomorphological imprint outside the Yorkshire Dales, where several large rain-on-snow floods were recorded (Merrett, 2001). Figure 7a shows a higher frequency of rain-on-snow floods in the UK uplands from 1760 to 1840 and during the 1890s, 1940s and 1980s; periods characterised by low average winter temperatures and a high frequency of cold winter months (Figure 7b). These decades are also picked out in lichen chronologies as flood-rich, especially the 1940s when several events occurred, culminating in the severe nation-wide 1947 floods. Decadally averaged winter temperatures have risen since 1780, especially since 1970 (Figure 7a), and there has been a corresponding reduction in snow cover and frost frequency in some upland areas of the UK (Holden and Rose, 2011). This explains, in part, the late 20th century decline in upland flooding due to a run of positive NAO winters (especially during the 1990s), despite the well-documented increase in upland winter rainfall over the same period (Burt and Ferranti, 2012). For small upland catchments the reduced frequency of snowmelt and associated extreme runoff appears to be of critical importance in the generation of fewer large floods.

Rain-on-snow floods do sometimes however occur during positive NAO phases (Table 3), typically during cold spells associated with W-NW winds following the passage of a depression; conditions that give snow cover on high ground in northern England (Johnson, 2005). Meteorological data (Table 3) show that: (i) rain-on-snow floods can be generated in association with modest temperature change (1995 and 2011; also see Archer, 1981); and (ii) very short cold snaps during otherwise mild winters (December 2011; Table 2, Table 3) can lead to serious flooding (Figure 4). Positive NAO winters are not always mild across the whole UK; for example, Kendon and McCarthy (2015) describe exceptionally deep and prolonged snow cover (mid-Dec to late-Feb) on the Scottish Mountains during the mild, wet and flood-rich winter of 2013/2014 (NAO 2.05). Although these snowy +NAO periods and associated floods are relatively uncommon, they add complexity that needs to be considered when interpreting long-term upland UK flood records in relation to the NAO index phase.

4.2. Extreme summer floods (boulder-berms)

Analysis of the SNAO series of Folland *et al*. (2009) shows that high rates of geomorphologically effective flooding in the second half of the 19th century, especially in the extremely wet 1870s (Burt *et al.*, 2014), clearly match a period of negative SNAO values, frequent cyclonic flow (Figure 8a) and high rainfall anomalies (Figure 8b). The early to mid-20th century peak of flooding recorded in all upland catchments is also characterised by pronounced negative SNAO, high rainfall anomalies and cyclonic flow frequency from 1915 to 1931 and from 1941 to 1966. Over the instrumental (1850-) and tree-ring (1441-1995) based records the SNAO has consistently low values before 1960, with a period of very pronounced and persistent negative SNAO values from 1770 to 1830 (Figure 8c). Analysis of July-August rainfall across England and Wales shows that 6 out of the 10 wettest summers on record occurred within this deeply negative SNAO window (for comparison, July-August rainfall in 2012 and 2007 rank 34th and equal 56th, respectively; July-August rainfall in 2004, the summer of the Boscastle flood, ranks equal 18th). This wet 1770-1830 period closely matches records of severe floods in northern England, especially the North Pennines (Figure 2).

As well as milder/wetter winters characterised by fewer rain-on-snow floods, reduced late 20th century upland flooding is also related to an unusual run of positive SNAO index values, strong negative rainfall anomalies and a marked decline in summer cyclonic flow. The latter is especially marked between 1961 and 1990 (Matthews *et al*., 2015) and corresponds with a reduction in heavy upland rainfall provided by cyclonic weather types (Burt and Horton, 2003; Burt and Ferranti, 2012). Such consistently positive SNAO values have not been recorded in the last 150 years and tree-ring reconstructions indicate they were last experienced in the early 16th century (Figure 8c; Folland *et al*., 2009; Linderholm *et al*., 2009). Since 1850 there has only been one other short period of positive SNAO values (1896-1904; Figure 8a) at the turn of the 20th century, which corresponds with a reduction in rainfall, cyclonic flow and upland flooding (Figure 2; Macklin and Rumsby, 2007). Given the importance of the SNAO on upland flood generation, the longer-term trend in declining flood magnitude since the late 19th/early 20th century is likely to have its origins in the fact that several long rainfall records show that summers were wetter (often wetter than winters) before the 20th century (*e.g*. Barker *et al*., 2004; Burt and Horton, 2007; Todd *et al*., 2015).

Between 2007 and 2012 the SNAO reverted to negative values, coincident with more frequent geomorphologically effective floods. Although the intensity of summer flooding during these five years came as a surprise to public and politicians alike in the UK, coming after several decades of relatively dry summers, neither the intensity nor duration of negative SNAO values was unprecedented (Figure 8). Deeper and more prolonged negative values occurred before 1960 when lichen-dated flood deposits show that major floods were more common. Historical data also suggest there is far more capacity in a fluctuating SNAO to produce wetter and more prolonged flood-rich periods than hitherto experienced in the early part of the 21st century. Our new geomorphological study chimes with the instrumental analyses of Lane (2008) and Burt and Ferranti (2012) that the increased frequency of flooding since 2007 should not have been unexpected in the context of long-term records.

4.4. Debris flow climatology

In contrast to extreme river channel floods, persistent low intensity rainfall is important in saturating slopes and triggering debris flows. These conditions are most likely during autumn and winter when positive correlations between the NAO and rainfall/river flows are strongest (Burt and Howden, 2013). Increased debris flow activity in the Cairngorms and Glencoe during the late 19th century corresponds with large positive summer, autumn and winter rainfall anomalies (Figure 9). High rates of debris flow activity in both areas from 1900 to 1960 are related to periods of high seasonal rainfall: 1900-1930 (spring), 1900-1960 (summer), 1910-1950 (autumn) and 1900-mid 1960s (winter) (Figure 9). Very high rates of debris flow activity in the 1970s appear to have been caused primarily by a sharp rise in autumn rainfall that peaked in the early 1980s. Some of the highest recorded rainfall anomalies between 1980 and 2010 are linked to strong and frequent positive NAO anomalies which post-date published Scottish lichen chronologies; it is likely that resurveying of Innes' (1983) original locations would show high rates of debris flow activity over the last 30 years or so. A high number of documented events since the late 1990s (Winter *et al*., 2010) would also support this contention.

As described in section 3.2 the An Teallach debris flow record differs appreciably from the other Scottish sites (Glencoe and Cairngorms). This is likely to reflect its location in a different extreme precipitation variability region (Figure 1), and the unusual positive correlation between summer rainfall, river flows and the station-based NAO index (Burt and Howden, 2013) in this region. In some cases, periods of very wet weather in eastern Scotland (and more widely in the UK) are not apparent in the far northwest of Scotland. For example, during April-June 2012 the Northwest Highlands and Islands experienced extremely dry conditions with record low flows on some rivers (CEH, 2012), in contrast to very wet conditions and severe flooding across the rest of the UK. Similar patterns are also evident for some very wet years during the 1870s (Burt *et al*., 2014). These differences are apparent in the Stornoway rainfall record in that periods of high summer rainfall in east Scotland are much less marked than further west (*e.g*. 1950s, late 2000s/early 2010s, Figure 9), and vice versa (*e.g*. 1980s). Peaks of debris flow activity in northern Scotland at *ca*. 1900 and *ca*. 1970 do reflect periods of anomalously high summer rainfall on Stornoway (Figure 9).

Short and spatially restricted debris flow records in Wales preclude a detailed analysis, although it is likely that the same hydroclimatic controls (*i.e*. prolonged periods of rainfall associated with +NAO phases) are critical in generating instability. There is generally only a weak relationship between precipitation in the Scottish regions and most parts of England and Wales (Gregory *et al*., 1991), which explains the difference in chronology of events.

5. 21st century stormy geomorphology and climate change

Our analysis shows that many severe 21st century floods experienced in many upland areas of the UK are not unprecedented. Nevertheless, following a relatively quiescent period in the incidence of extreme events since 1960, renewed severe flooding that began again in 2007 has had major impacts on society, in some cases due to increased vulnerability through inappropriate floodplain development (Stevens *et al*., 2014). As extreme upland floods in small catchments tend to be generated by localised torrential downpours, it is unlikely that landuse or farming practices are major contributing factors. We would therefore question the economics and use of simplistic ecosystem services approaches to flood mitigation through small-scale afforestation programmes (e.g. Carroll *et al*., 2004).

Is anthropogenic climate change also to blame for increased flood frequency? The NAO/SNAO has fluctuated markedly over the last few centuries and recent very wet summers are not unusual in an historical context. However, the underlying causes of exceptionally wet historical summers and those of recent years need not necessarily be the same. For example, there is growing evidence of a causal link between recent observed Arctic sea-ice anomalies, large scale atmospheric circulation and wet summers in Europe (Screen, 2013). Rapid Arctic warming relative to Northern Hemisphere or globe as a whole - so called Arctic amplification - may also be responsible for creating a 'wavier' jet stream (Francis and Vavrus, 2015), which leads to persistent weather patterns associated with extreme events, including wet summers and cold winters.

6. Practical applications

Despite the call of Macklin and Rumsby (2007) nearly 10 years ago for the use of sedimentary flood data in upland flood risk assessment in the UK, the methods discussed in this paper are still restricted to academic studies, despite their use in other areas of the world in mainstream flood risk management (Jarrett and Tomlinson, 2000). Palaeoflood data can be used to characterise the largest 'geomorphologically effective' events and compute unit discharges for catchments of a given size, significantly improving flood magnitude envelope curves (Figure 10a) for use in the design of flood management structures (*e.g.* flood walls/embankments, reservoir outflow/overspill features). Palaeoflood approaches are especially useful for characterising discharges in very small catchments (<1 km^2), which tend to be data poor. They are also invaluable for extending the flood series beyond the instrumental record. For example, Figure 10b shows annual maximum flow data for the Afon Leri in Wales, which experienced a large flood in summer 2012 (Foulds *et al*., 2014b). Before 2012 a gauged flow of 40 m^3 s^{-1} would have been considered a large flood; without a geomorphological analysis the 2012 flood might have been called a rare/very rare event. However, documentary archives record a similar event as recently as June 1935, and inclusion of palaeoflood data suggests it was of a similar magnitude to 2012 (see Foulds *et al*., 2014b).

7. Conclusions

Geomorphologically inferred flood records can be used contextualise recent hydrometeorological ‘extremes’, which are often erroneously reported as ‘unprecedented’. Our new analysis of torrential sedimentary deposits reveals that 21st century floods are not unprecedented, although some recent floods have equalled or exceeded the largest recorded events. A combination of the winter NAO (as defined by Jones *et al*., 1997) and summer NAO (as defined by Folland *et al*., 2009) controls the timing and magnitude of extreme upland floods in the UK through two flood generating mechanisms: winter rain-on-snow events and torrential summer downpours. These conditions are associated with negative index values in both seasons and the recent upturn in upland flooding is related to a marked negative phase of the summer NAO between 2007 and 2012. Historical climate data also suggest there is greater capacity in the North Atlantic climate system to produce wetter and more prolonged flood-rich periods than hitherto experienced in the 21st century. Rapid warming of the Arctic in recent years would appear to favour the generation of persistent weather types that cause extreme events (Francis and Vavrus, 2015).

Climate change, and the likely increasing incidence of extreme flooding in poorly monitored upland UK catchments, necessitates that geomorphologically informed risk assessments become an important part of flood protection policy. At present, as also noted by Knight and Harrison (2013), this is not the case. Earth surface system dynamics contextualise and control the overall response to climate forcing (Knight and Harrison, 2013), and the exclusion of non-systematic flood data such as that provided by the fluvial sedimentary archive in risk studies is a major oversight. This situation has arisen due to the reluctance of the flood risk management community (traditionally dominated by engineers and hydrological statisticians in the UK) to go beyond the ‘comfort zone’ of short instrumental records because of the difficulty of applying standard statistical methods and a perceived increase in data uncertainty. Although flood risk practitioners may feel more secure by following conventional flood risk assessment protocols, using instrumental or extrapolation of instrumental data, multi-centennial length geomorphic-based flood records presented in this paper demonstrate that reliance solely on the mid-late 20th Century flood series is underestimating current flood risk in the UK uplands. Of equal importance is the present lack of a standardised and accessible geomorphological approach that can be used by flood risk managers in the UK. The production of a 'geomorphological flood risk assessment handbook', similar to the widely used *Flood Estimation Handbook* for hydrological data, would greatly improve the wider understanding and dissemination of geomorphologically-based approaches in flood risk analysis. A more integrated approach is clearly needed to manage and mitigate the impacts of future climate change and extreme floods in the UK uplands as well as in similar areas worldwide.

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Table 1. Catchment physiography, nature and chronology of flood deposits in UK upland study areas

Upland region	Drainage area of studied catchments (km^2)	Geology	Type of flood deposit	Particle size (mm)	Lichen used for dating	Maximum length of flood record (yrs)	Date of largest flood event	Extreme precipitation region (after Jones *et al.* 2014)	Author(s)
An Teallach	<1	Sandstone	Debris flow	0.44 (mean bulk sample)	*Section Rhizocarpon, Rhizocarpon alpicola*	240	No information	North Highland & Islands	Innes 1983
Cairngorms	<1	Granite	Debris flow	2.22 (mean bulk sample)	As above	590	No information	East Scotland	Innes 1983
Glencoe	<1	Andesite Granite Rhyolite	Debris flow	1.58-2.43 (mean bulk sample)	As above	190	No information	South Scotland	Innes 1983
Northern Pennines	8-20	Sandstone Shale	Boulder berm	250-750 ($\bar{x}$ 10 largest clasts)	*Rhizocarpon geographicum agg., Porpidia tubercolosa*	230	1766	North West	Rumsby 1991, Macklin *et al.* 1992
Lake District	<1	Andesite Rhyolite Slate	Boulder berm	250-1400 ($\bar{x}$ 5 largest clasts)	*Rhizocarpon spp.*	231	1749	Solway	Carling 1997, Johnson & Warburton 2002
Yorkshire Dales	0.3-11	Sandstone Limestone	Boulder berm	300-1000 ($\bar{x}$ 5 largest clasts)	*Rhizocarpon geographicum agg. Porpidia tubercolosa, Aspicilia calcarea*	327	1771 or 1795	Northwest	Merrett & Macklin 1999, Merrett 2001
Snowdonia	<1	Siltstone Mudstone Rhyolite Sandstone Basalt Dolerite	Debris flow	Photographs indicate boulder-size material	*Rhizocarpon geographicum subsp. prospectans*	140	No information	North West	Winchester & Chaujar 2002
Cambrian Mountains	<10	Slate Sandstone	Boulder berm	270-840 ($\bar{x}$ 5 largest clasts)	*Rhizocarpon geographicum agg., Porpidia tubercolosa*	151	1923/1962	Mid Wales	Foulds *et al.* 2014a

Brecon Beacons (Black Mountain)	4	Sandstone	Boulder berm	500-1400 ($\bar{x}$ 10 largest clasts); 300-1300 ($\bar{x}$ 5 largest clasts)	*Rhizocarpon concentricum; Rhizocarpon geographicum agg.*	248; 243	1827; 1841	Mid Wales	Shufflebottom 2003; Salisbury 2009
Brecon Beacons (Central Beacons)	1-6	Sandstone	Boulder berm	260-630 ($\bar{x}$ 5 largest clasts)	*Rhizocarpon geographicum agg., Porpidia tubercolosa*	124	2008	Mid Wales	Matthews 2015
Dartmoor	0.7-24	Granite	Boulder berm	220-1490 ($\bar{x}$ 3 largest clasts)	*Rhizocarpon geographicum agg., Porpidia tubercolosa, Pertusaria corallina, Pertusaria aspergilla*	288	1864	South West	Foulds *et al.* 2014b

Table 2. The five largest floods in the Swale catchment (North Yorkshire) at Catterick (piedmont, 1992-2013) and Grinton (stage only; uplands, 1996-).

River Swale at Catterick			
Rank	Date	Stage (m)	Q (m^3 s^{-1})
1	25th Sep 2012	3.547	506.547
2	31st Jan 1995	3.476	484.172
3	4th Jun 2000	3.244	416.247
4	8th Dec 2011	3.161	393.261
5	6th Sep 2008	3.144	388.639

River Swale at Grinton			
Rank	Date	Stage (m)	
1	8th Dec 2011	2.935	-
2	25th Sep 2012	2.681	-
3	7th Feb 2001	2.511	-
4	20th Sep 2000	2.501	-
=5	19th Feb 1997	2.461	-
=5	6th Sep 2008	2.461[2]	-

[2] Note in original data file: 'Top end correction of 57mm. Drift applied. Data marked as suspect'

Table 3. Meteorology of documented positive NAO rain-on-snow floods. NAO values are shown for the month of flood and previous month in brackets. A 10 day synoptic history is also shown (*italics* = day of flood); where detailed meteorological data are available (1995 and 2011), maximum and mean daily temperatures (T_{min} + T_{max}/2) at Moor House in the North Pennines (556 m elevation) are shown (bold values indicate days with snow lying in the vicinity of an automatic weather station). Documentary data are taken from Merrett (2001; 1835-1984 floods), CEH (1995) and Darlington and Stockton Times (2011).

Flood date	Upland area	NAO	10 day synoptic history (Lamb weather type; max/mean daily temperature)										Flood details
11/03/1835	Y. Dales	1.54 (3.37)	-	-	-	-	-	-	-	-	-	-	Great snow, thaw and flood; 2 people drowned.
17/02/1910	Y. Dales	3.85 (2.57)	*CSW*	W	C	SW	SW	SW	W	SW	A	N	Rapid thaw accompanied by heavy rain and sleet.
01/01/1925	Y. Dales	4.23 (3.86)	*SW*	W	W	SW	CW	CSW	CSW	SW	SW	SW	Heavy gale and rain; thaw of snow.
Feb 15th-17th 1950	Y. Dales	3.31 (0.55)	*SW*	W	CN	CSW	C	C	W	W	SW	NW	Heavy rain and gales aggravated by snowmelt.
Jan 1984	Y. Dales	2.53 (0.83)	-	-	-	-	-	-	-	-	-	-	Extended thaw after heavy snowfalls for a week.
31/01/1995	Y. Dales/N. Pennines/L. District	2.70 (2.86)	*SW* 6.40; 3.10	**A** **-0.60**; **-3.55**	**C** **2.00**; **-0.25**	**C** **2.90**; **2.05**	**S** **2.40**; **-1.95**	**N** **-1.50**; **-3.35**	**C** **-0.30**; **-1.10**	W 0.90; 0.15	**CNW** **1.00**; **-0.25**	**C** **-0.30**; **-1.00**	Notable 2-day rainfall totals augmented by significant snowmelt produced exceptional flows.
08/12/2011	Y. Dales	3.20 (0.74)	*C* 5.65; 2.77	NW 1.82; 0.58	**W** **1.64;** **-0.42**	**NW** **-0.91;** **-1.41**	NW 0.64; -0.74	W 6.38; 3.71	W 6.39; 3.62	W 5.17; 2.84	SW 5.21; 3.35	CW 8.66; 4.81	Heavy rain combined with melting snow; some of the worst flooding in living memory.

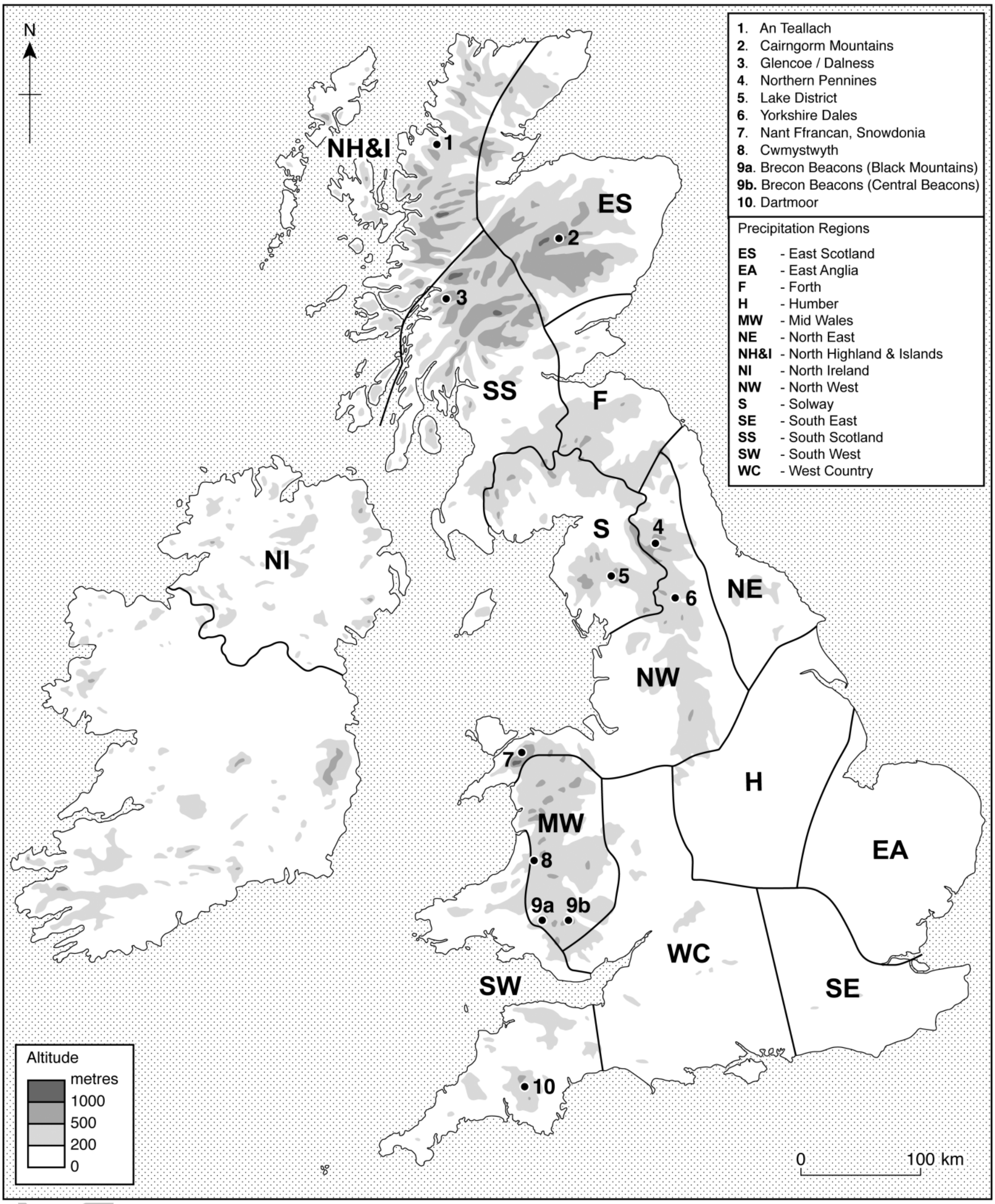

Figure 1. Location of lichen-dated flood deposits in upland Great Britain. Extreme precipitation variability regions (after Jones et al., 2014) are also shown.

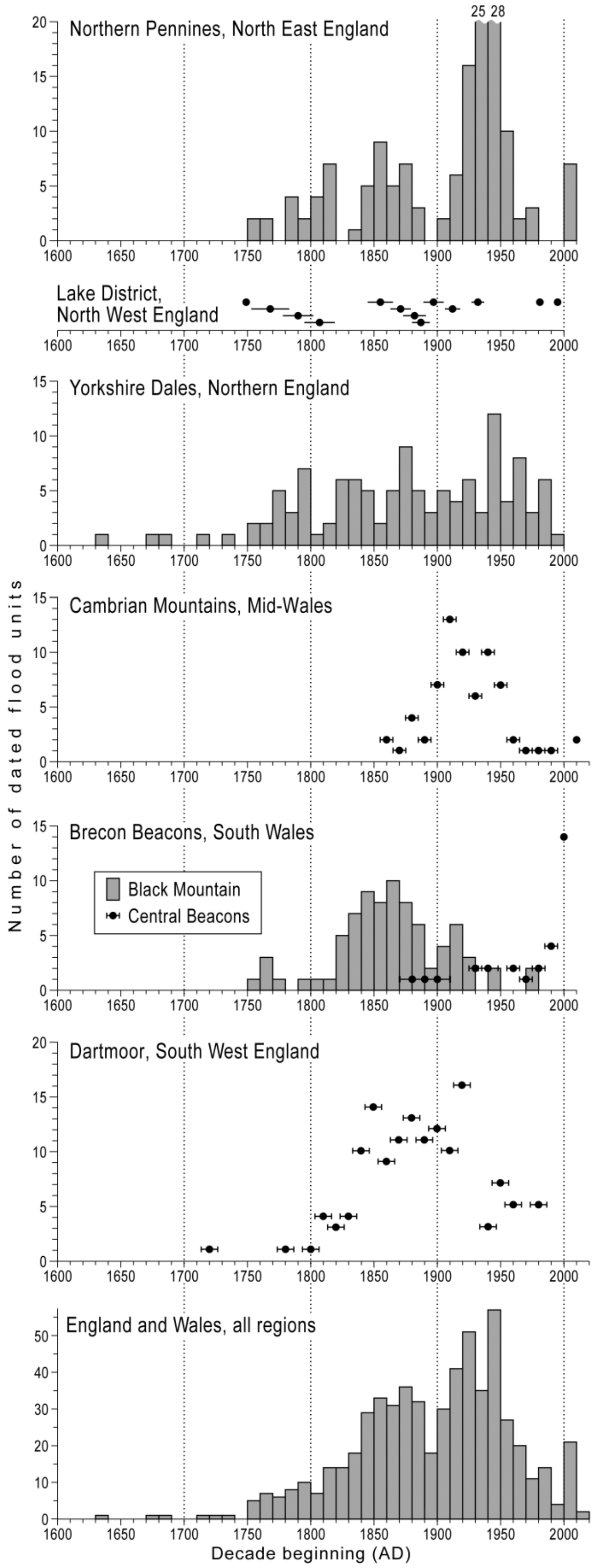

Figure 2. Decadal frequency of lichen-dated boulder-berms in upland areas of England and Wales. Where available (Dartmoor, Cambrian Mountains and Central Brecon Beacons) lichen dating accuracy is indicated by +/- 2σ error bars; for full details see Foulds et al., 2014a, 2014b and Matthews, 2015).

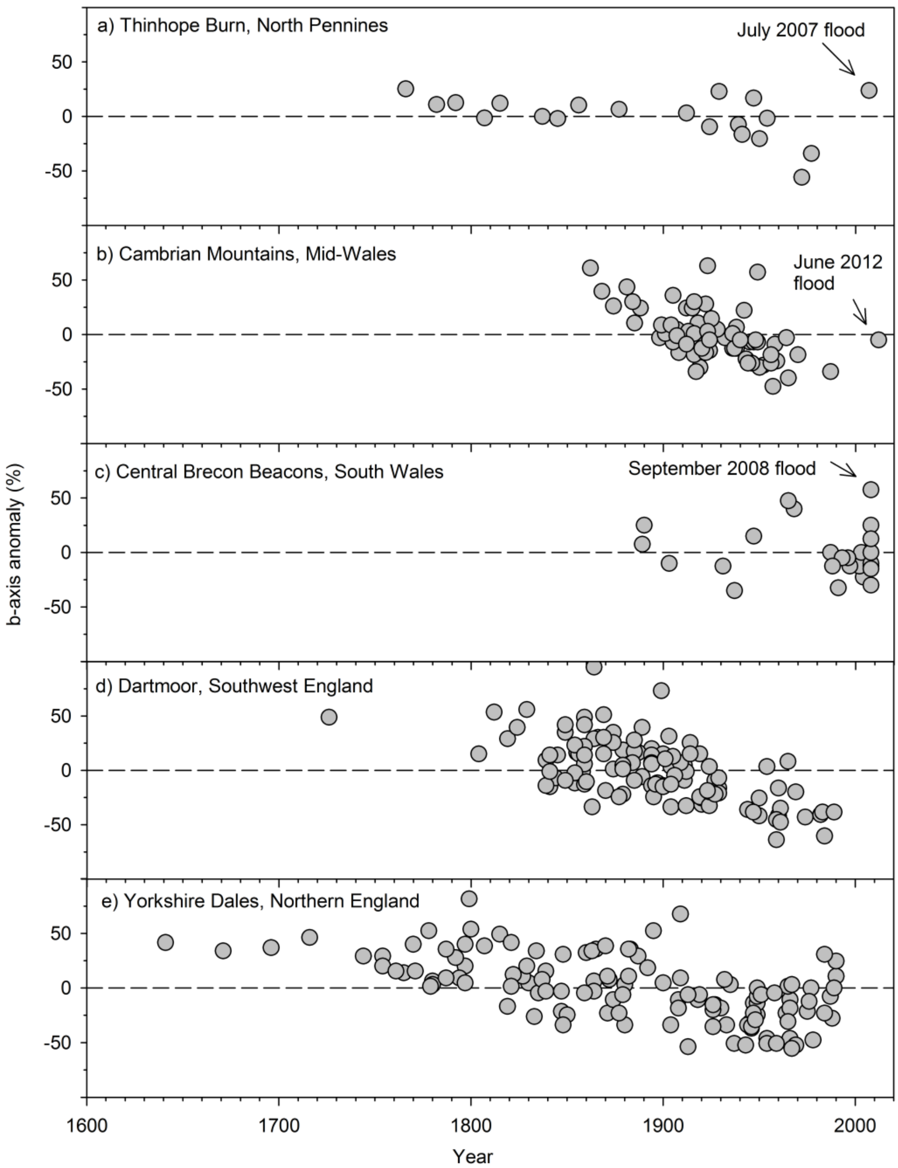

Figure 3. Relative flood magnitude based on average boulder-berm b-axis measurements. '0' on the y-axis (dashed line) represents the average size of boulders moved by extreme floods in each study catchment.

Figure 4. Upper Swaledale during the December 2011 rain-on-snow flood (note the hill-side torrents and remaining snow patches on high ground). Photographs by Jill Armstrong (Swaledale Mountain Rescue Team).

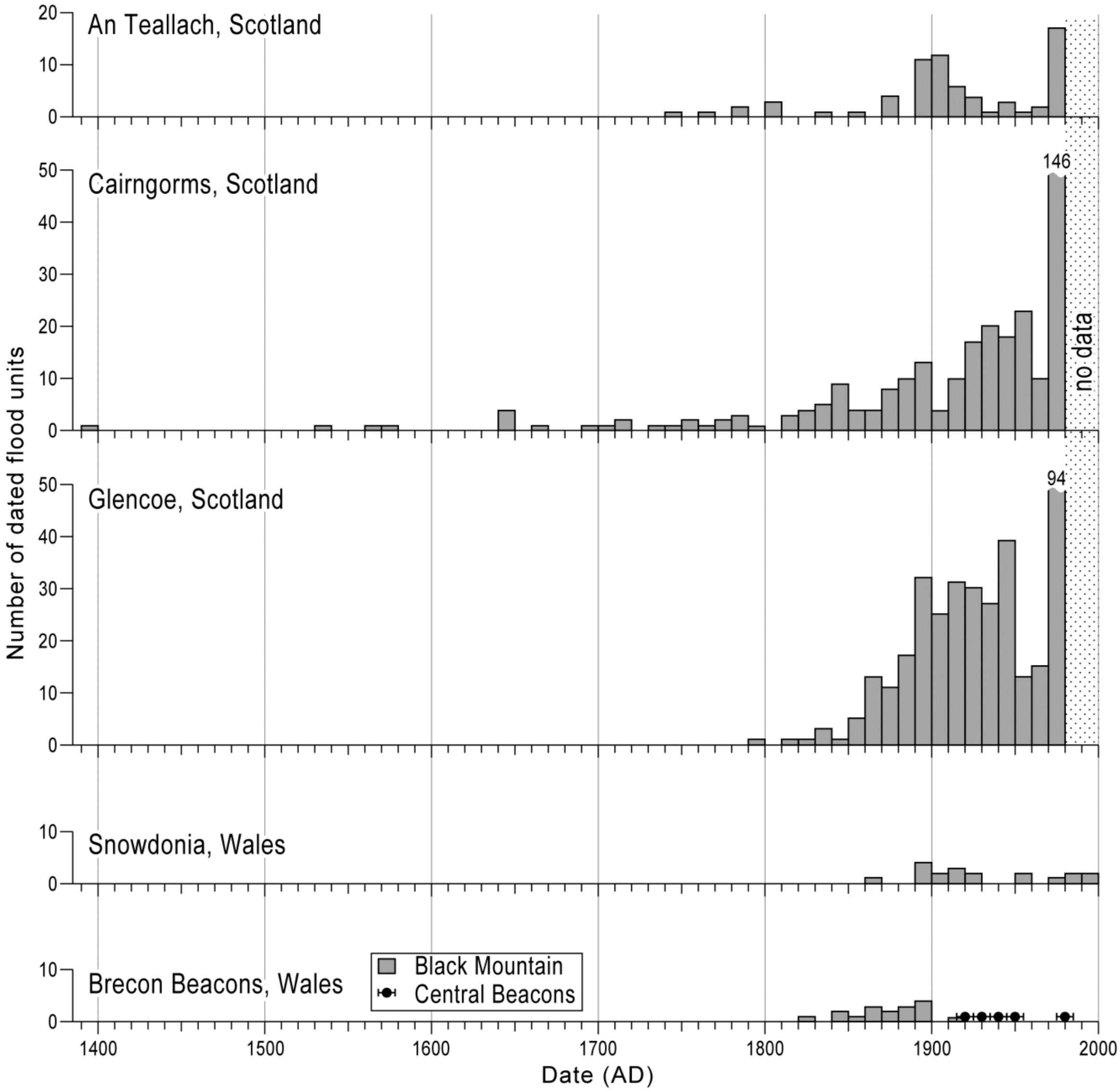

Figure 5. Decadal frequency of lichen dated debris flows in upland areas of Scotland and Wales. For the Central Brecon Beacons lichen dating accuracy is indicated by +/- 2σ error bars (see Matthews, 2015).

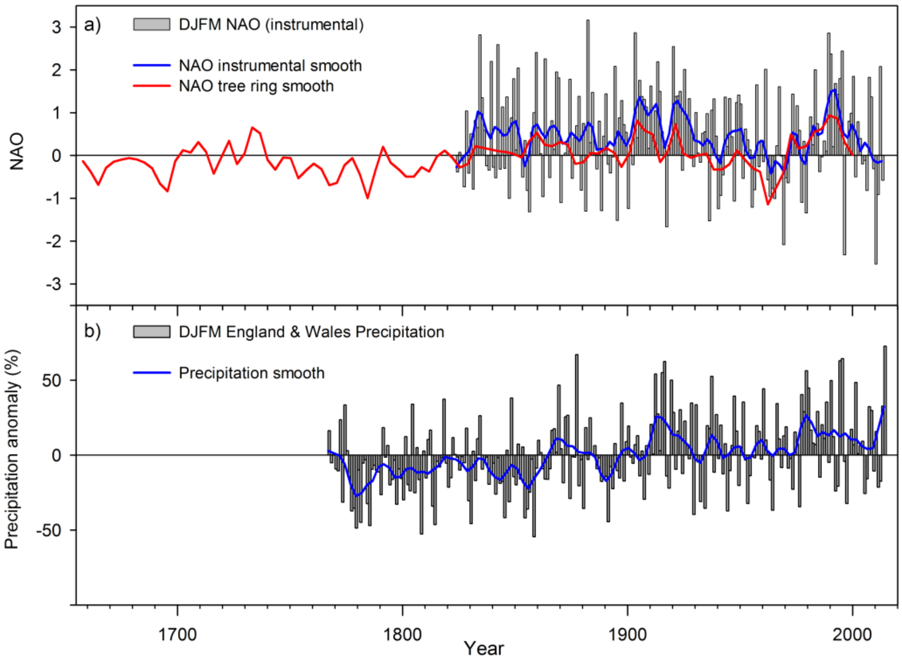

Figure 6. (a) Instrumental winter NAO (DJFM) data (1822-2013) (Jones et al., 1997; Osborn, 2011) plotted alongside a winter NAO tree ring reconstruction (Luterbacher et al., 2001); (b) England and Wales winter rainfall anomalies (1766-2014) (Alexander and Jones, 2000).

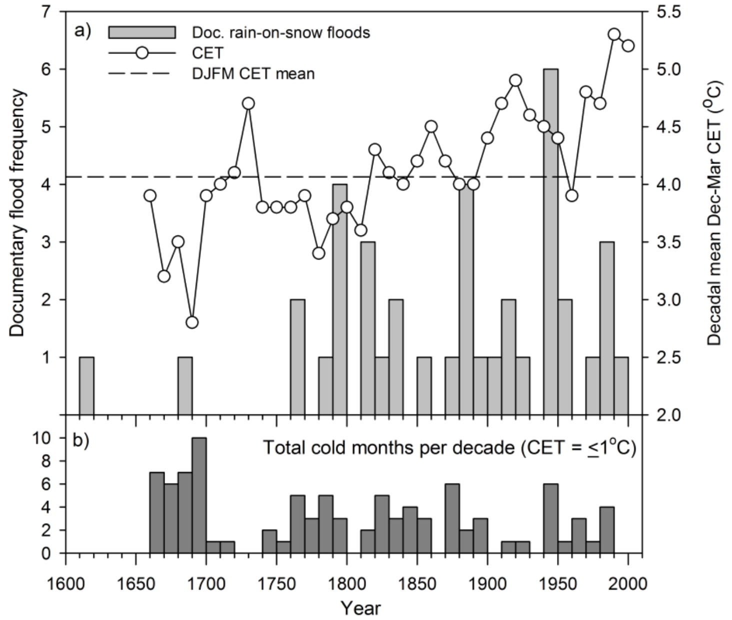

Figure 7. (a) Decadal mean winter temperature of central England (Parker et al., 1992) plotted alongside the decadal frequency of documented rain-on-snow floods in upland England and Wales; (b) Decadal frequency of cold winter months (DJFM) in central England, defined here as a mean monthly temperature of <1oC.

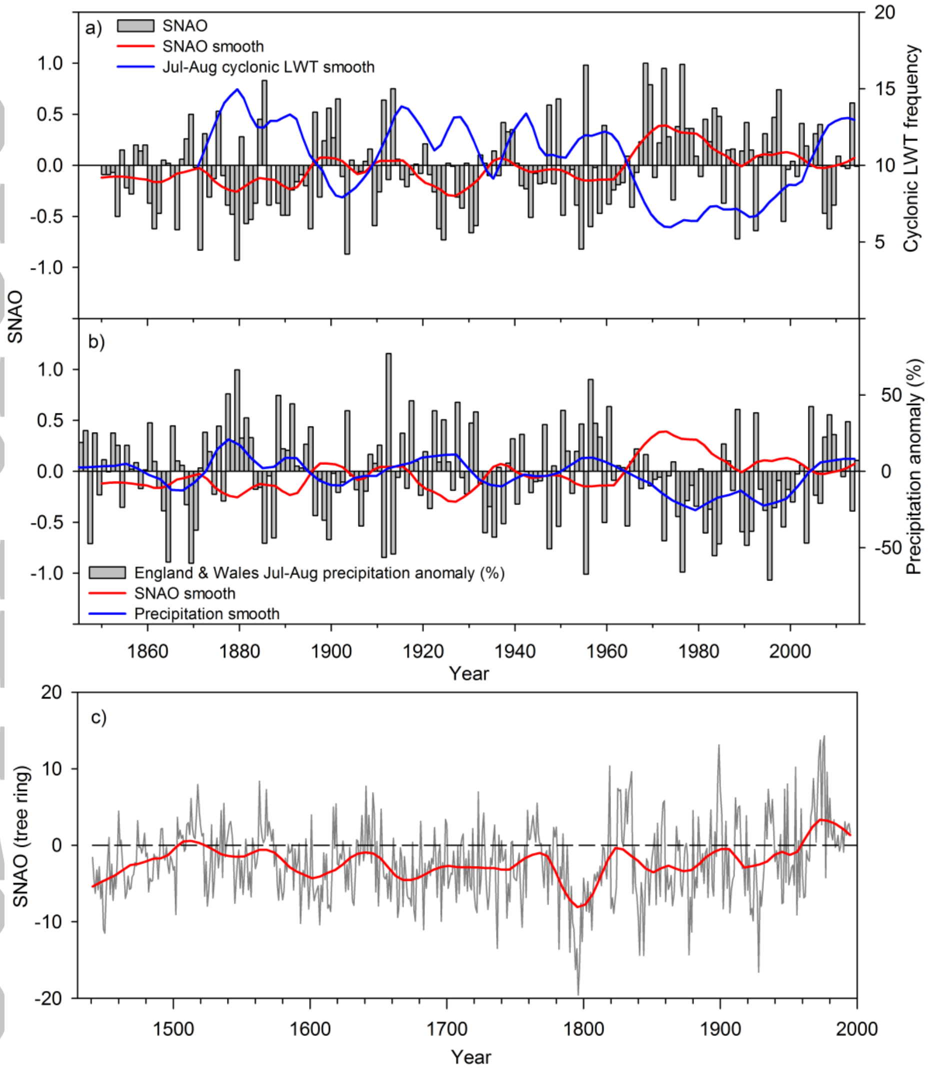

Figure 8. (a) High summer (July-August) SNAO (Folland et al., 2009) and the frequency of July-August cyclonic Lamb weather types (Jones et al., 2013); (b) Smoothed SNAO plotted alongside July-August rainfall anomalies in England and Wales; (c) Tree ring reconstruction of the SNAO (1441-1995; Linderholm et al., 2009).

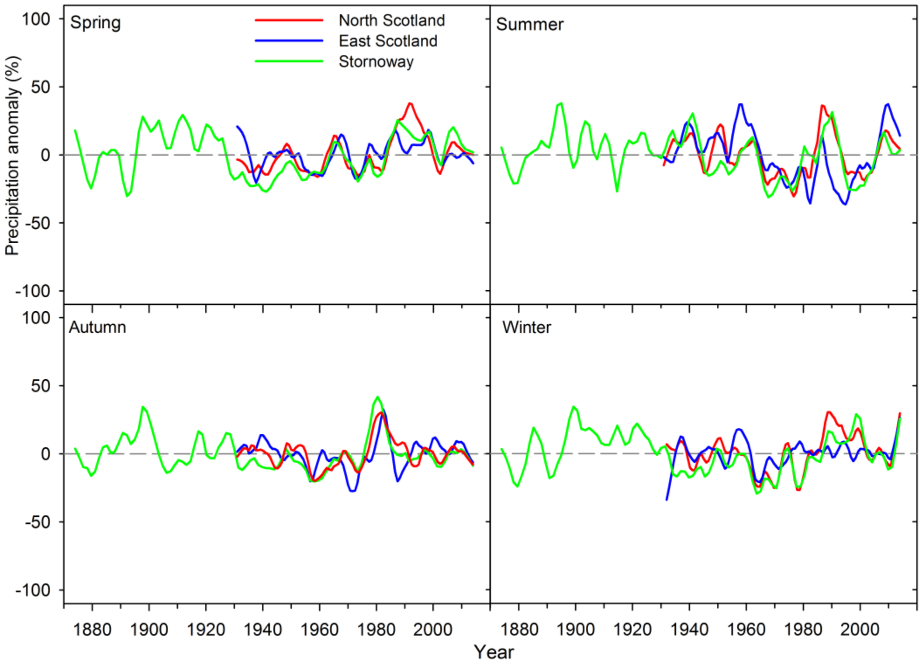

Figure 9. Smoothed seasonal rainfall anomalies for north and east Scotland (1931-2013), and Stornoway (1873-2013).

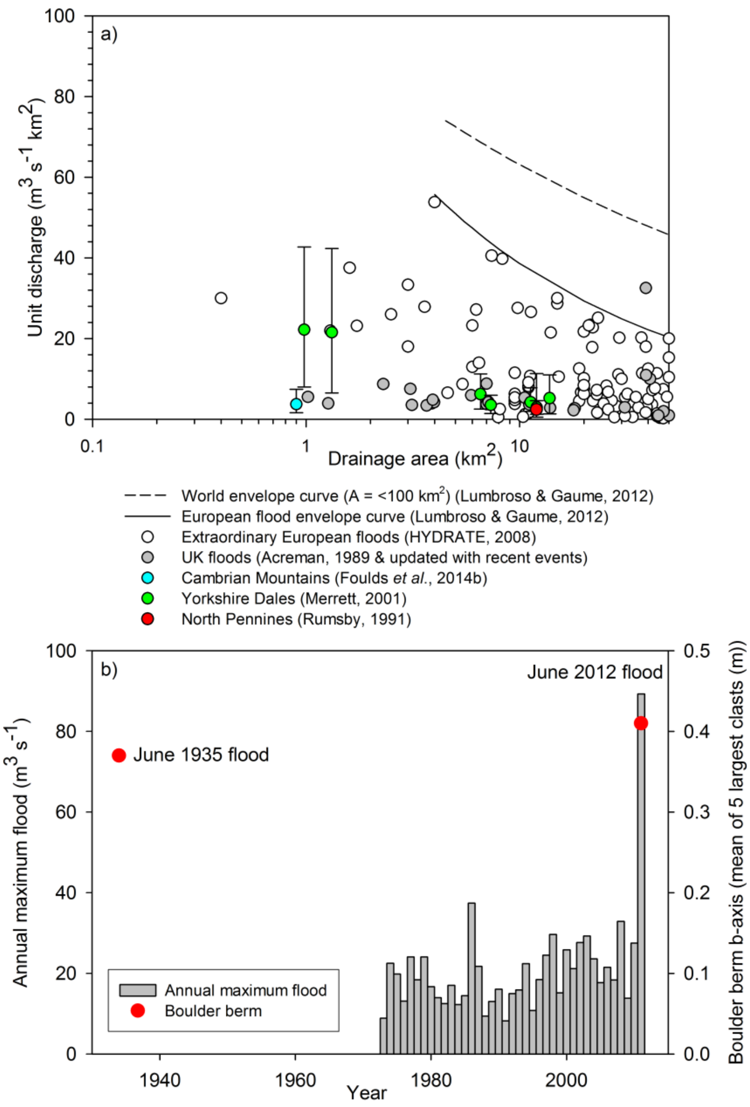

Figure 10. (a) Unit discharge of extreme upland floods based on geomorphological data, plotted alongside other UK and European data; (b) annual maximum flow and boulder-berm data for the Afon Leri (Wales).